NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1538

ANALYSIS OF ACCURACY OF GAS-FILLED BELLOWS

FOR SENSING GAS DENSITY

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Washington
February 1948

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SUMMARY

An analysis is presented of the characteristics of gas-filled bellows for sensing gas density to delineate the factors that affect the accuracy of this type of bellows. An equation is developed that indicates the effect of changes in the pressure and the temperature to which the bellows is subjected on the gas-density — bellows-displacement characteristics. An equation is also developed that determines the effect of a change in each of the bellows-design constants on the error of density indication.

For minimum error, the bellows should be as flexible as possible (low spring rate) and the bellows area (or diameter) should be as large as possible. The bellows filling volume (volume of gas in bellows at position of no stress in bellows) and filling density (density of gas in bellows at position of no stress in bellows with bellows mechanically locked in this position) may then be adjusted to cause the bellows to indicate the desired range of density.

INTRODUCTION

In many control applications, the control equations include the density of a gas. For example, the equation for air flow through a head meter includes the air density; the equation for air velocity as measured by a pitot tube involves air density; and the equations defining the power output and the required fuel flow of reciprocating and gas-turbine engines involve an air density. In control mechanisms that solve equations of these types, density-sensitive devices must therefore be incorporated to provide an indication of the gas density.

Because the density of a gas is determined by the ratio of the absolute pressure to the absolute temperature, the indication of density may be obtained from the proper division of the indications from absolute-pressure-sensitive and absolute-temperature-sensitive devices. For example, the indications from a pressure-sensitive bellows and from a temperature-sensitive bellows could

be mechanically divided to obtain a true indication of the density.
Many such devices can be conceived, all of which involve separate
elements for sensing pressure and temperature and require mechan-
ical, hydraulic, or electrical division of the indications to
obtain an indication of density.

Because of the complexity of such devices, their use may be
unjustified except in certain control applications where good
accuracy over an extreme density range is required. In many con-
trol applications, the need for good accuracy extends only over a
limited range, and design considerations may dictate the use of a
simple, inexpensive density-sensitive element. For applications
of this type, the gas-filled density-sensitive bellows may be a
satisfactory choice. Inherent errors of indication, however, exist
with this type of bellows. Because the accuracy of the complete
control mechanism, of which the density-sensitive bellows is a part,
is affected by the accuracy of the density-sensing element, and
because of the incentive to use this type of density-sensitive
element, an analysis that determines the cause of errors and the
means of reducing them should be of value in the design of this
type of control device.

Such an analysis was therefore made at the NACA Cleveland
laboratory. Expressions are derived for the density-displacement
characteristics (density of the gas surrounding the bellows as
indicated by the linear expansion, or displacement, of the bellows)
and for the error of the density indication. The factors that
cause the error are analyzed and means are suggested for reducing
the error.

ANALYSIS

Characteristic Equation of a Gas-Filled Bellows

A diagram of a typical density-sensitive bellows is presented
in figure 1(a). The bellows is filled with a dry gas (usually
nitrogen). Such a bellows responds to the pressure outside the
bellows and the temperature around the bellows assembly. For
analysis, this bellows system may be reduced to the equivalent
system involving spring rates, volumes, areas, pressures, and so
forth shown in figures 1(b) and 1(c) if the following assumptions
are made:

1. The volume of the bellows is proportional to the linear
displacement.

2. The spring rates of the bellows and of the external spring are constant over the displacement range and are unaffected by temperature variations.

3. The areas over which the internal and external pressures are effective are equal (or in a constant ratio) and are constant over the bellows-displacement range.

In the equivalent system, the spring action of the bellows is represented by the two equal spring rates S_b on opposite sides of the piston of area A, which represents the diaphragm area of the bellows. The external spring, which is often used in mechanisms of this type, is represented by the spring rate S_e. When no external spring is used, the spring rate S_e is considered zero; when the external spring acts in the opposite direction to that shown in figure 1(a), the direction of the force exerted by this spring is reversed. The force that the bellows must exert to actuate a control mechanism is represented by F. In this analysis, F is considered positive when its direction tends to compress the bellows. The position x of figure 1(b) is the point at which the bellows is unstressed. The displacement D (fig. 1(c)) is measured from this position (considered positive in the direction in which the bellows is compressed); and the filling volume V_f (volume of gas inside bellows), the preloading distance (or deflection) of the external spring L, and the filling density ρ_f (density of gas inside bellows) are determined at this position. The filling density is considered to be measured with the bellows mechanically locked in the position x, so that the effects of the external forces are eliminated. This method in effect then actually determines the weight of gas in the bellows.

Consider the case in which the pressure outside the bellows is raised to some absolute pressure P and the temperature of the system is lowered to some absolute temperature T. The bellows then assumes some position y (fig. 1(c)) and the following equation applies:

$$PA+S_e(L-D)+F = P_yA+S_bD \qquad (1)$$

where

P pressure outside bellows (absolute)

A effective area of bellows acted upon by pressure inside and outside bellows

S_e spring rate of external spring

L   preloading distance of external spring

D   displacement of bellows from position x

F   external force on bellows assembly

P_y pressure inside bellows at position y (absolute)

S_b spring rate of bellows

The pressure P_y can be related to the initial pressure conditions by the gas-law equation

$$\frac{P_y V_y}{T} = \frac{P_f V_f}{T_f}$$

where

V_y volume inside bellows at position y

T   temperature of system (absolute)

P_f filling pressure (absolute)

V_f filling volume

T_f filling temperature (absolute)

(The temperatures inside and outside the bellows are assumed equal.)

Solving for P_y gives

$$P_y = \frac{P_f V_f T}{V_y T_f}$$

With the assumption that the bellows volume is proportional to the displacement,

$$V_y = V_f - AD$$

and

$$P_y = \frac{P_f V_f T}{T_f (V_f - AD)} \qquad (2)$$

Substituting this expression for P_y in equation (1) results in

$$PA+S_e(L-D)+F = \frac{P_f V_f TA}{T_f(V_f-AD)} + S_b D$$

The solution for P gives

$$P = \frac{P_f V_f T}{T_f(V_f-AD)} + \frac{1}{A}\left[S_b D - S_e(L-D)-F\right] \qquad (3)$$

Inasmuch as

$$P_f/T_f = \rho_f R_i$$

where

ρ_f bellows filling density

R_i gas constant for gas inside bellows

equation (3) becomes

$$P = \frac{R_i \rho_f V_f T}{V_f-AD} + \frac{1}{A}\left[S_b D - S_e(L-D)-F\right] \qquad (4)$$

Equation (4) expresses the relation of the bellows displacement to the pressure outside the bellows for various temperatures. The relation of bellows displacement to the density outside the bellows is determined as follows: The pressure P outside the bellows may be expressed as

$$P = \rho T R_o$$

where

ρ density of the gas outside bellows

R_o gas constant of gas outside bellows

Equation (4) then becomes

$$\rho T R_o = \frac{R_i \rho_f V_f T}{V_f-AD} + \frac{1}{A}\left[S_b D - S_e(L-D)-F\right]$$

Solving for ρ results in

$$\rho = \frac{R_1 \rho_f V_f}{R_0(V_f - AD)} + \frac{1}{R_0 TA}\left[S_b D - S_e(L-D) - F\right] \tag{5}$$

For a given bellows assembly, all the terms of equation (5) are constant except ρ, D, T, and F. The displacement of a bellows of this type thus is obviously not a true indication of external gas density because the indication is parametric with the temperature T and with the external force F. Because $T = P/\rho R_0$, equation (5) can obviously be expressed with pressure as the parameter instead of temperature,

$$\rho = \frac{R_1 \rho_f V_f}{R_0(V_f - AD)\left\{1 - \frac{1}{PA}\left[S_b D - S_e(L-D) - F\right]\right\}} \tag{6}$$

Thus the density-displacement curves are parametric with either the temperature T or the pressure P and with the external force F.

When the external spring S_e is so reversed that it acts in the opposite direction to that shown in figure 1, the direction of the force exerted by this spring is reversed, which changes the sign of the term $S_e(L-D)$ in equation (1), and the direction of preloading is also reversed so that the term $L-D$ becomes $L+D$. Equations (4), (5), and (6) then become

$$P = \frac{R_1 \rho_f V_f T}{V_f - AD} + \frac{1}{A}\left[S_b D + S_e(L+D) - F\right] \tag{7}$$

$$\rho = \frac{R_1 \rho_f V_f}{R_0(V_f - AD)} + \frac{1}{R_0 TA}\left[S_b D + S_e(L+D) - F\right] \tag{8}$$

and

$$\rho = \frac{R_1 \rho_f V_f}{R_0(V_f - AD)\left\{1 - \frac{1}{PA}\left[S_b D + S_e(L+D) - F\right]\right\}} \tag{9}$$

The effect of temperature T and pressure P on the density-displacement curves of a bellows with nitrogen inside the bellows

and air outside and with the configuration of figure 1 is shown in
figure 2. The curves were plotted from equations (5) and (6) with
the following values of the various bellows constants:

A, square inches 2.0
S_b, pounds per inch 50.0
S_e, pounds per inch 20.0
L, inches 0.4
ρ_f, pounds per cubic foot 0.05
V_f, cubic inches 4.0
F, pounds 2.0

With the units of ρ_f and ρ in pounds per cubic foot, the units
of the gas constant become feet per °R. The values of R_i and R_o
were taken at 55.2 and 53.3 feet per °R, respectively.

Equation for Bellows Error

An expression for the error of indication of the bellows at
any temperature and density may be obtained from the equation for
the density-displacement characteristics by the following method:
The mechanism operated by a bellows assembly is assumed to be so
calibrated that the correct density is indicated at some calibra-
tion temperature T_c, as shown in figure 3. At any actual tem-
perature T_a (either higher or lower than T_c), the bellows fol-
lows the T_a curves. However, each displacement indicates a
density ρ_c on the T_c curve, whereas the actual density ρ_a
that caused the displacement is found on the T_a curves. The
error may then be represented as

$$\frac{\rho_a - \rho_c}{\rho_c} = error$$

The expression for $\rho_a - \rho_c$ may be obtained from equation (5) as
follows:

$$\rho_a - \rho_c = \frac{R_1 \rho_f V_f}{R_0 (V_f - AD)} + \frac{1}{R_0 T_a A} \left[S_b D - S_e (L - D) - F \right]$$

$$- \frac{R_1 \rho_f V_f}{R_0 (V_f - AD)} - \frac{1}{R_0 T_c A} \left[S_b D - S_e (L - D) - F \right]$$

$$= \frac{T_c - T_a}{R_0 A T_a T_c} \left[S_b D - S_e (L - D) - F \right]$$

The expression for $\dfrac{\rho_a - \rho_c}{\rho_c}$ then becomes

$$\frac{\rho_a - \rho_c}{\rho_c} = \frac{\dfrac{T_c - T_a}{A T_a T_c} \left[S_b D - S_e (L - D) - F \right]}{\dfrac{R_1 \rho_f V_f}{V_f - AD} + \dfrac{1}{A T_c} \left[S_b D - S_e (L - D) - F \right]} \tag{10}$$

When the external spring S_e acts in the opposite direction, equation (8) is used and the equation for error becomes

$$\frac{\rho_a - \rho_c}{\rho_c} = \frac{\dfrac{T_c - T_a}{A T_a T_c} \left[S_b D + S_e (L + D) - F \right]}{\dfrac{R_1 \rho_f V_f}{V_f - AD} + \dfrac{1}{A T_c} \left[S_b D + S_e (L + D) - F \right]} \tag{11}$$

METHODS OF REDUCING BELLOWS ERROR

An examination of equation (10) indicates that, for a bellows designed to operate over finite ranges of density and of temperature, the error can be reduced to zero only by making the term $\left[S_b D - S_e (L - D) - F \right]$ equal zero. The appearance of this term in the equation for error of the bellows (equation (10)) furnishes a clue to the reason why error exists in this type of bellows. The units of the term $\left[S_b D - S_e (L - D) - F \right]$ are force units and the term is composed entirely of spring forces and external forces exclusive of gas-pressure forces. This term therefore obviously represents the resultant force due to the spring forces and external load. Because the bellows is always in equilibrium, it is evident that this term

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also represents the gas-pressure difference across the area A necessary to equal the resultant of the spring forces and external load. A difference in density must therefore exist between the inside and the outside of the bellows that depends on the pressure difference and the temperature of the bellows system. Because the pressure difference is a function of the displacement, this density difference is a function of the displacement and of the temperature of the bellows system. From equation (2), the density inside the bellows may be shown to be a function of the displacement only. Because the sum of the inside density and the density difference is equal to the outside density, the displacement is plainly a function not only of the outside density but also of the temperature (or pressure, equation (6)) of the system, because of the existence of the spring forces and the external force.

Although a finite value for the term $\left[S_b D - S_e(L-D) - F\right]$ causes the error of the bellows, it is not the only factor affecting bellows error once a finite value for this term exists. Equation (10) indicates that each of the bellows-design constants $(A, S_b, S_e, V_f, L, \text{ and } \rho_f)$, the force F, the temperatures T_c and T_a, and the gas constant R_1 all have an effect on the error. Because the term $\left[S_b D - S_e(L-D) - F\right]$ cannot practicably be made zero (a limp diaphragm or a piston as in fig. 1 could be used in place of the bellows but such systems are impractical because of leakage), the specific effect of each of the bellows-design constants on bellows error must be determined in order to set up the design principles for design of a bellows with minimum error.

The effect on error of each of the bellows-design constants, $A, S_b, S_e, V_f, L, \text{ and } \rho_f$, and of the external force F, is shown in figures 4 to 10 for $T_c = 520^\circ$ R and $T_a = 400^\circ$ R together with the corresponding density-displacement curves for $T_c = 520^\circ$ R, which illustrate the effect of a change in each of the design constants on the density-displacement characteristics. Figure 6 also shows the effect of reversing the external spring S_e so that it acts in the opposite direction from that shown in figure 1. For this reversal, the equation for error is equation (11). All the curves are terminated at the point at which the displacement in the positive direction (negative direction for the case of the external spring S_e reversed) is equal to the preloading distance L of the external spring. The effect of the gas constant R_1 is omitted, because the choice of gases is limited, because the variation in the constants of suitable gases is small, and because the effect on error of a change in R_1 is the same as a similar percentage change in ρ_f.

An examination of figures 4 to 10 indicates that for an
independent change in most of the design constants the density
range for a given displacement range is changed. Because for a
given bellows assembly the displacement range must be kept within
practical limits to avoid overstress of the bellows, the effect
of a change in each of the design constants on the density range
for a given displacement range must also be considered. Table I
is a comparison of the effect of a change in each of the design
constants and in the external force F on bellows error and on
the density range. In many instances, it is difficult to deter-
mine whether a particular change in a design constant causes a
reduction or an increase in error when the entire density range
is considered. In these cases, the designer must be guided by the
fact that any reduction in the force that the bellows must over-
come because of the bellows spring rate or other mechanical forces
tends to reduce the error, because, as will be noted from the fore-
going equations, the error is roughly indicated by the ratio of the
total force that the bellows must oppose to the area of the bellows.

The conclusion to be drawn from figures 4 to 10 and table I
is that the rates of springs S_b and S_e and the external force F
should be reduced and that the bellows area should be made large.
In order to compensate for the decrease in density range caused by
these changes, the filling volume V_f must be reduced. The filling
density ρ_f (which has little effect on error) may then be adjusted
to orient the bellows to the desired density range. In most appli-
cations elimination of the external spring S_e (which also elimi-
nates the preloading distance L) is feasible and in some applica-
tions (where servoamplifiers are used) elimination of the external
force F is possible. These changes materially simplify all the
characteristic equations and reduce the error. Because low values
of filling volume are desirable in order to reduce the error and
to compensate for the effect on the density range of changes in
spring rates and area, and because low bellows spring rates and
large areas are associated with bellows of large volume, the
bellows may have to be filled partly with a nonvolatile liquid in
order to secure the desired values of filling volume. Adherence
to these principles will ensure design of a bellows of minimum
error.

CONCLUDING REMARKS

An analysis of the characteristics and the error of a gas-
filled bellows for sensing gas density shows that a density-sensitive

bellows does not give a true indication of density but one that is parametric with the conditions of temperature or pressure. The existence of temperature or pressure as a parameter is caused by the force that the bellows must oppose. In an actual bellows assembly this force is composed of the spring forces of the bellows, the forces of any external springs that may be used, and the output force required of the bellows. The amount of error is roughly indicated by the ratio of the total force that the bellows must oppose to the area of the bellows. Bellows for this application should then be designed with as low spring rates as possible and the output force required of them should be as low as possible. Because the reduction of the bellows spring rate is limited in practice, the diaphragm area of the bellows should be made as large as possible. Selection of the proper values of filling volume (volume of gas in bellows at position of no stress in bellows) and filling density (density of gas in bellows at position of no stress in bellows with bellows mechanically locked in this position) may then be used to cause the bellows to cover the desired density and displacement ranges. In the choice of proper values of filling volume and filling density, the advantage for reduction of error lies with low values of filling volume because filling density has relatively little effect on error. In order to secure the low values of filling volume with the large diaphragm areas and low spring rates desirable the bellows may have to be filled partly with a relatively nonvolatile liquid. Compliance with these design principles will ensure a bellows with minimum error.

Flight Propulsion Research Laboratory,
      National Advisory Committee for Aeronautics,
            Cleveland, Ohio, September 23, 1947.

TABLE I - COMPARISON OF EFFECT OF EACH OF DESIGN CONSTANTS AND EXTERNAL FORCE

ON ERROR AND DENSITY RANGE OF BELLOWS

Design constant	Direction of change in design constant	Apparent effect on error	Apparent effect on density range
Area, A	Increase	Decrease	Decrease
Bellows spring rate, S_b	Decrease	Decrease	Decrease
External spring rate, S_e	Decrease	Decrease	Decrease
Filling volume, V_f	Decrease	Decrease	Increase
Preloading of external spring, L	Decrease	Indeterminate; should decrease in general	Parallel shift to higher density
Filling density, ρ_f	Decrease	Indeterminate	Parallel shift to lower density
External force, F	Decrease	Indeterminate; should decrease in general	Parallel shift to higher density

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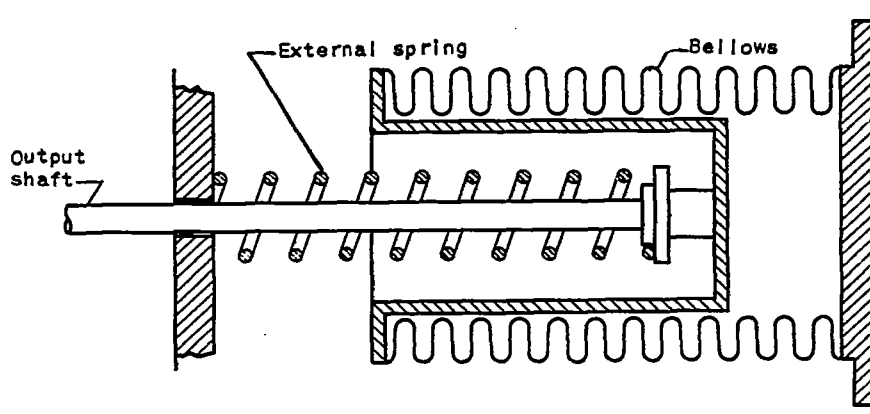
(a) Typical density—sensitive bellows.
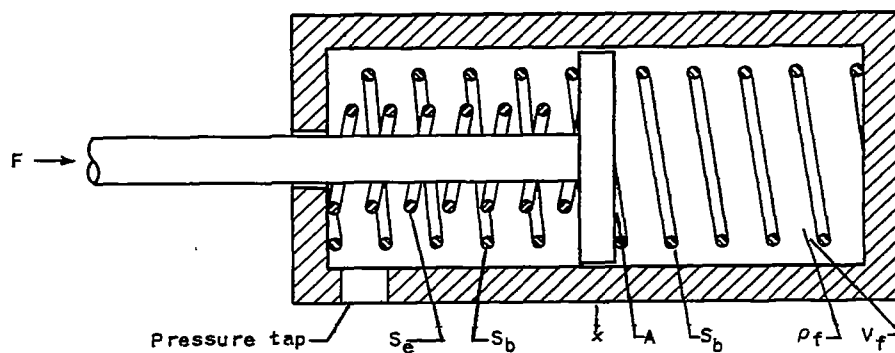
(b) Equivalent system at position x.
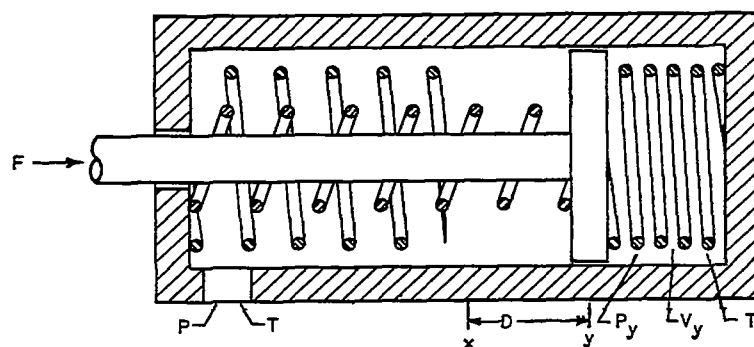
(c) Equivalent system at position y.

Figure I. — Typical density-sensitive bellows and equivalent system.
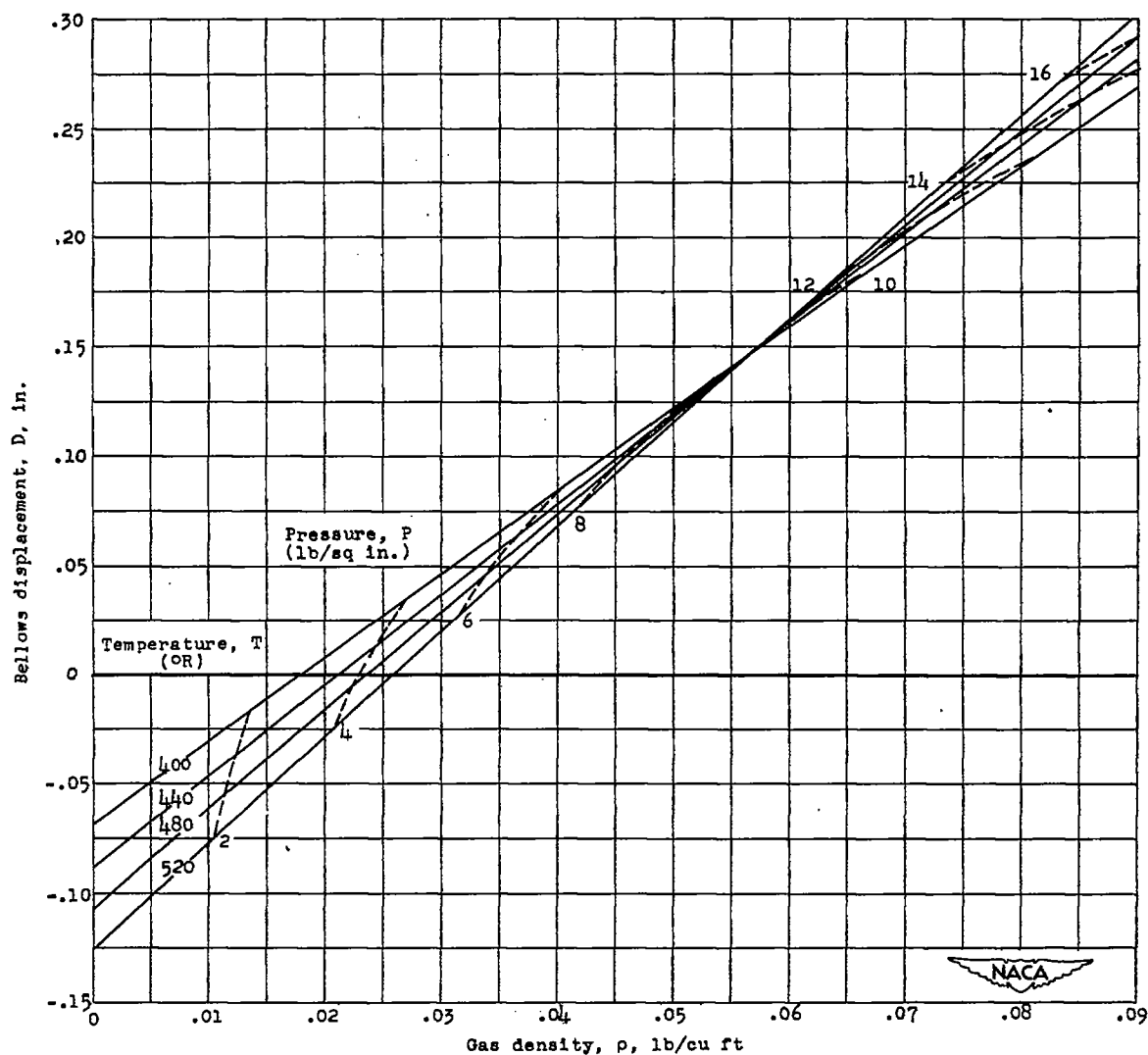
Figure 2. — Effect of temperature and pressure on gas-density — bellows-displacement characteristics of density-sensitive bellows. Nitrogen-filled bellows sensing air density; bellows area A, 2 square inches; bellows spring rate S_b, 50 pounds per inch; external spring rate S_e, 20 pounds per inch; preloading distance of external spring L, 0.4 inch; filling density ρ_f, 0.05 pound per cubic foot; filling volume V_f, 4 cubic inches; external force F, 2 pounds; gas constant of gas inside bellows R_i, 55.2 feet per °R; gas constant of gas outside bellows R_o, 53.3 feet per °R.
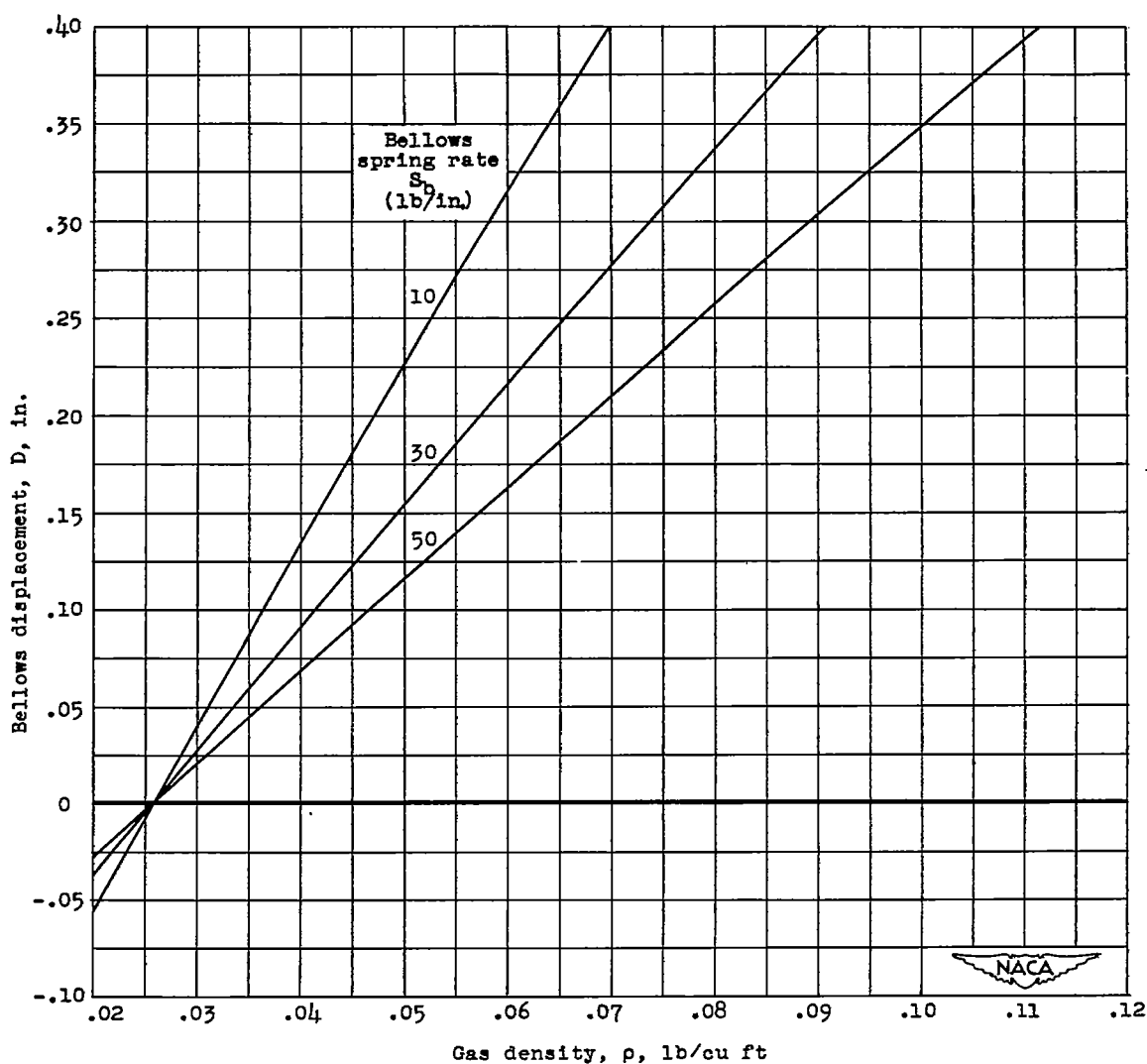
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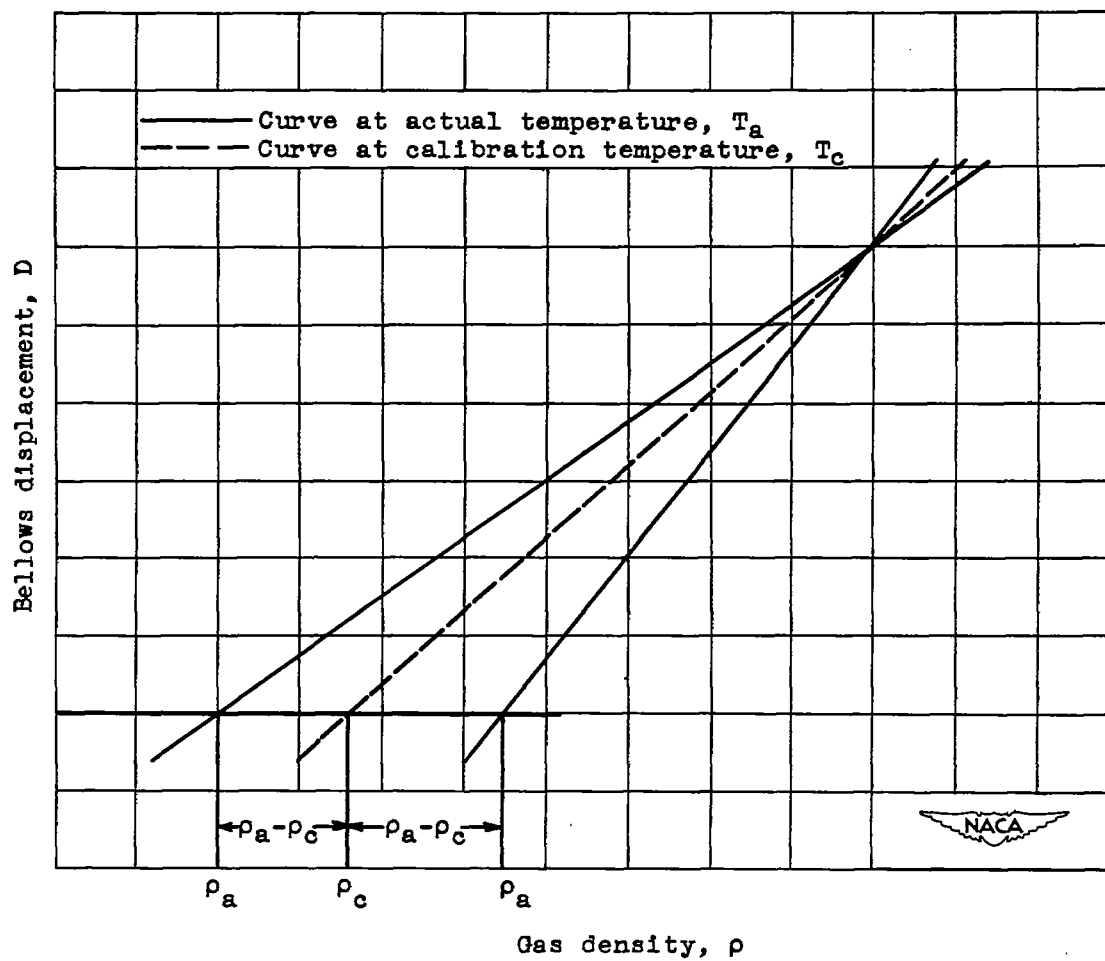
Figure 3. — Characteristic curves illustrating bellows error.
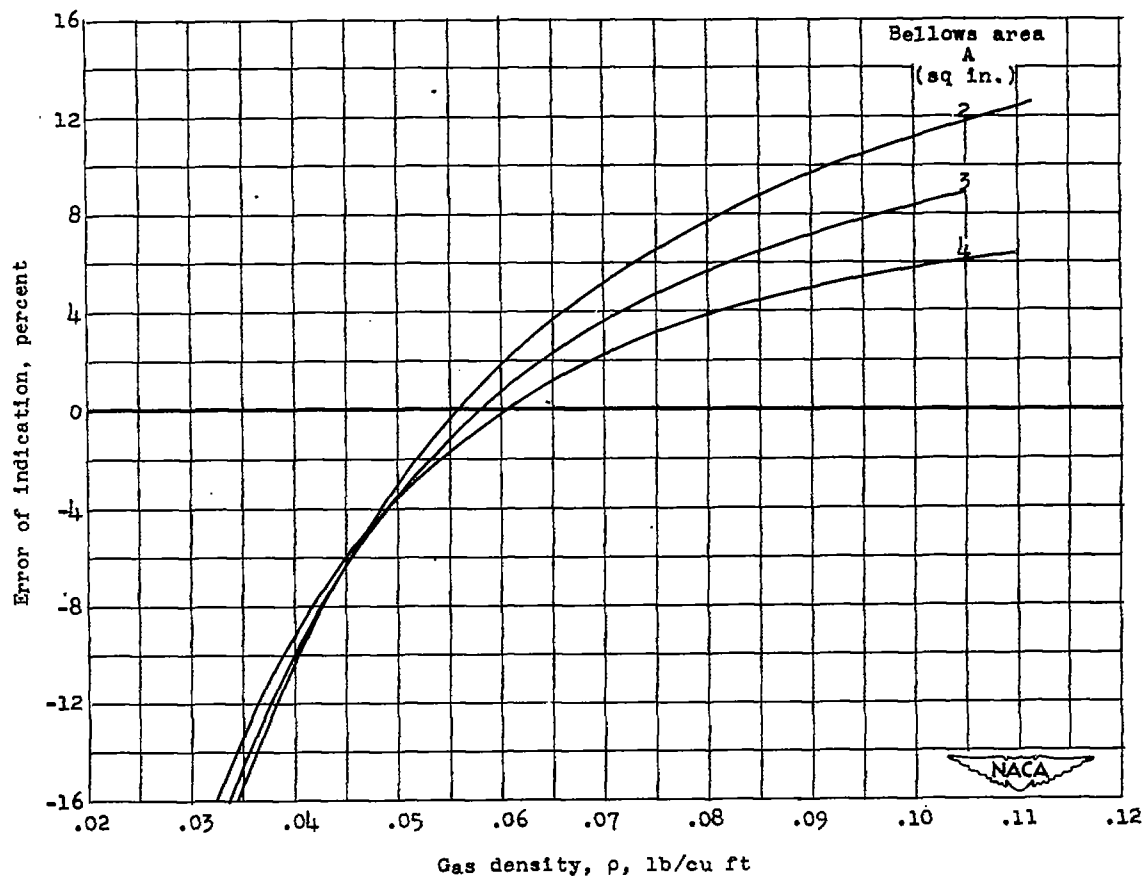
(a) Error of indication; calibration temperature T_c, 520° R; actual temperature T_a, 400° R.

Figure 4. — Effect of independently varying bellows area on error of indication and gas—density — bellows-displacement characteristics. Bellows spring rate S_b, 50 pounds per inch; external spring rate S_e, 20 pounds per inch; preloading distance of external spring L, 0.4 inch; filling density ρ_f, 0.05 pound per cubic foot; filling volume V_f, 4 cubic inches; external force F, 2 pounds; gas constant of gas inside bellows R_i, 55.2 feet per °R; gas constant of gas outside bellows R_o, 53.3 feet per °R.
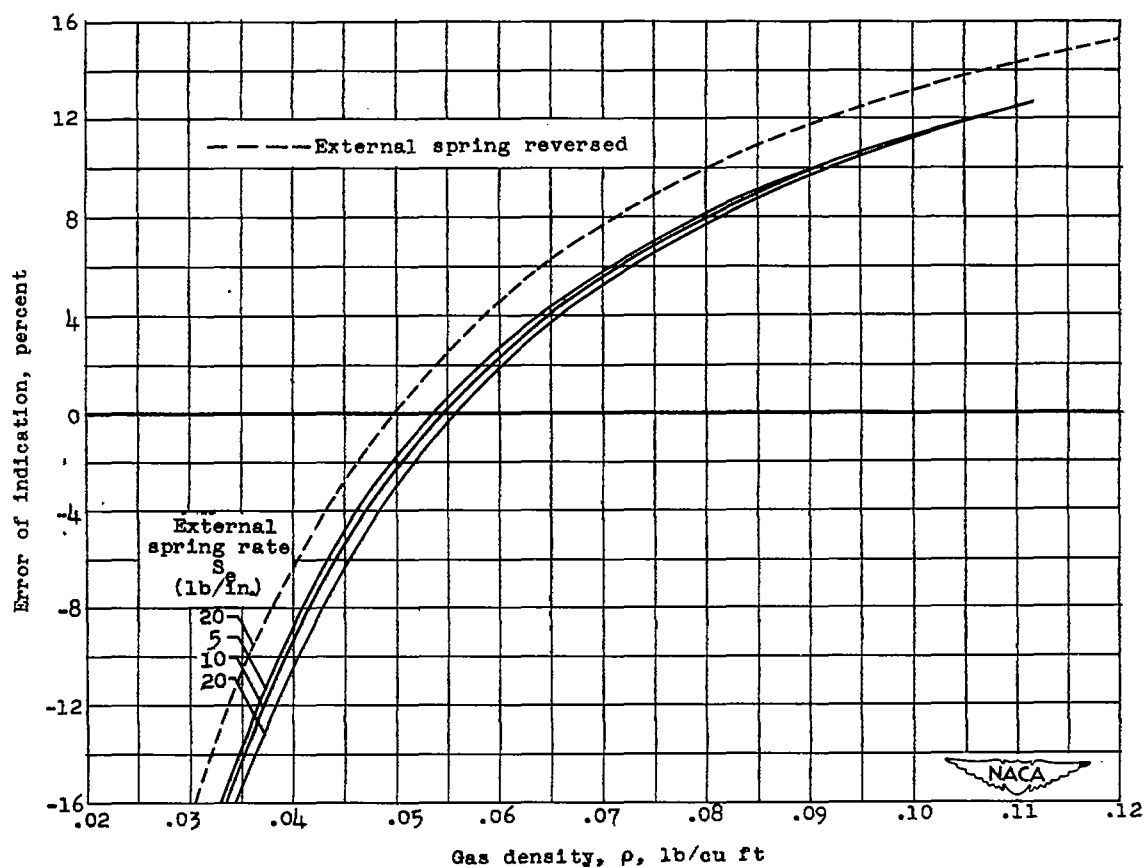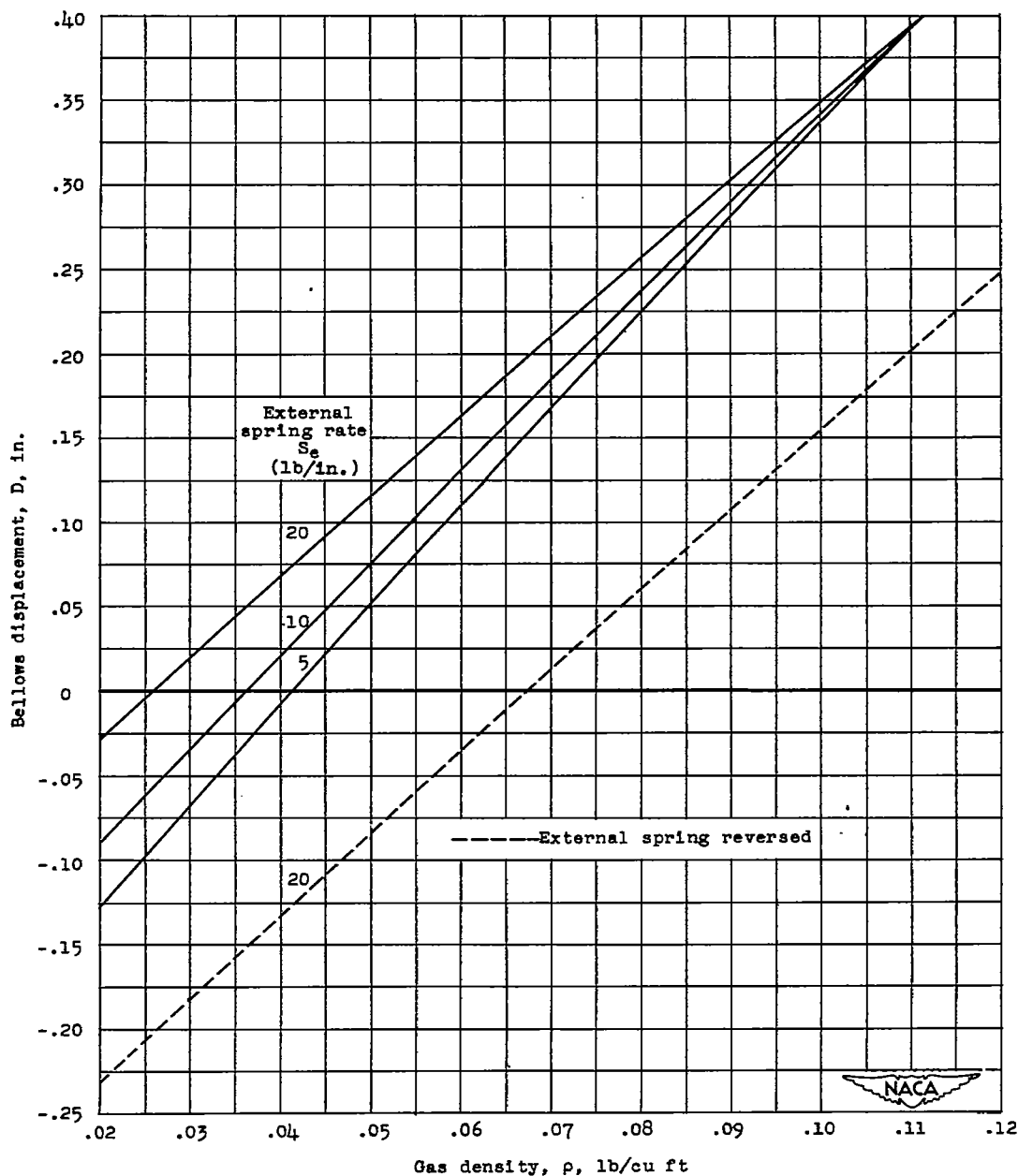
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(b) Gas-density - bellows-displacement characteristics at calibration
temperature T_c, 520° R.

Figure 4. — Concluded. Effect of independently varying bellows area on
error of indication and gas—density — bellows—displacement character—
istics. Bellows spring rate S_b, 50 pounds per inch; external spring
rate S_e, 20 pounds per inch; preloading distance of external spring
L, 0.4 inch; filling density ρ_f, 0.05 pound per cubic foot; filling
volume V_f, 4 cubic inches; external force F, 2 pounds; gas constant
of gas inside bellows R_i, 55.2 feet per °R; gas constant of gas out—
side bellows R_0, 53.3 feet per °R.
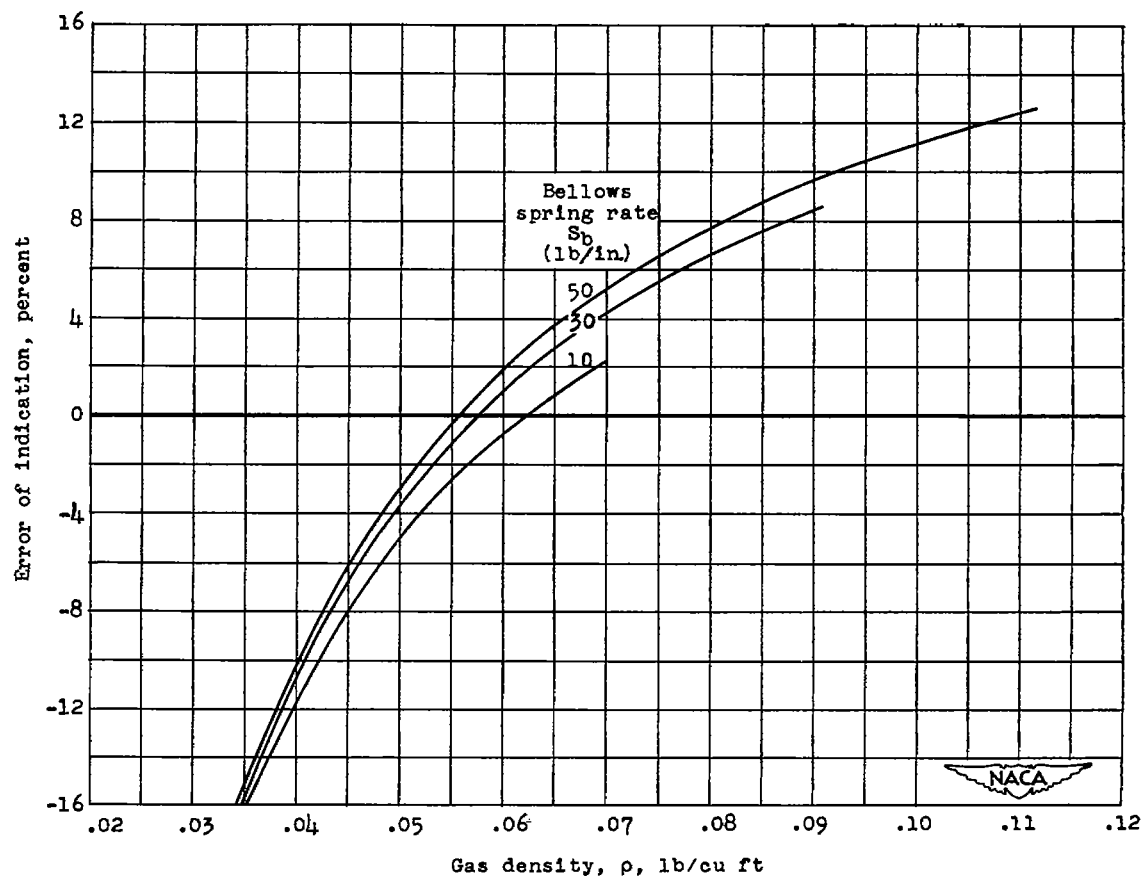
(a) Error of indication; calibration temperature T_c , 520° R; actual temperature
T_a , 400° R.

Figure 5. — Effect of independently varying bellows spring rate on error
of indication and on gas–density–bellows–displacement characteristics.
Bellows area A, 2 square inches; external spring rate S_e , 20 pounds

per inch; preloading distance of external spring L, 0.4 inch; filling
density ρ_f , 0.05 pound per cubic foot; filling volume V_f , 4 cubic

inches; external force F, 2 pounds; gas constant of gas inside bellows
R_i , 55.2 feet per °R; gas constant of gas outside bellows R_o ,
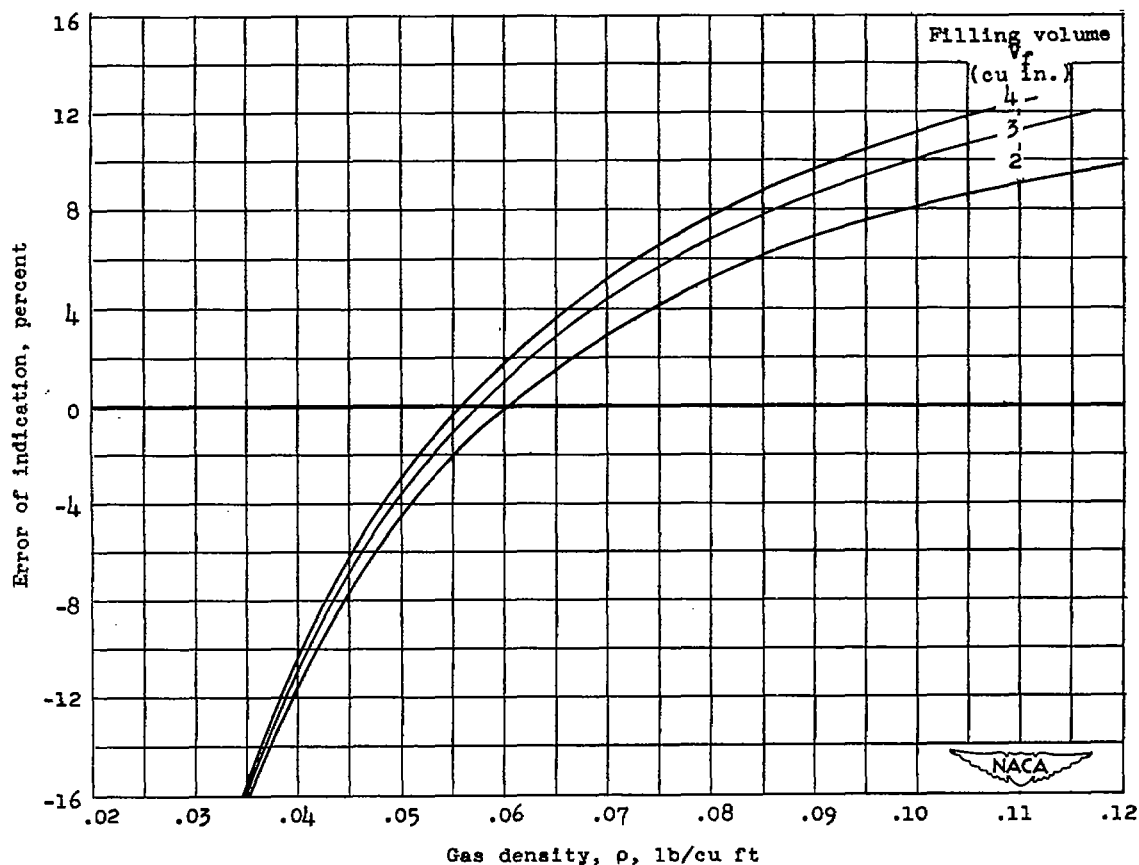
53.3 feet per °R.

(b) Gas-density – bellows-displacement characteristics at calibration
temperature T_c, 520° R.

Figure 5. – Concluded. Effect of independently varying bellows spring
rate on error of indication and on gas–density – bellows–displacement
characteristics. Bellows area A, 2 square inches; external spring
rate S_e, 20 pounds per inch; preloading distance of external spring
L, 0.4 inch; filling density ρ_f, 0.05 pound per cubic foot; filling
volume V_f, 4 cubic inches; external force F, 2 pounds; gas constant
of gas inside bellows R_i, 55.2 feet per °R; gas constant of gas out-
side bellows R_o, 53.3 feet per °R.

(a) Error of indication; calibration temperature T_c, 520° R; actual temperature T_a, 400° R.

Figure 6. — Effect of independently varying external spring rate on error of indication and on gas-density — bellows-displacement characteristics. Bellows area A, 2 square inches; bellows spring rate S_b, 50 pounds per inch; preloading distance of external spring L, 0.4 inch; filling density ρ_f, 0.05 pound per cubic foot; filling volume V_f, 4 cubic inches; external force F, 2 pounds; gas constant of gas inside bellows R_i, 55.2 feet per °R; gas constant of gas outside bellows R_o, 53.3 feet per °R.
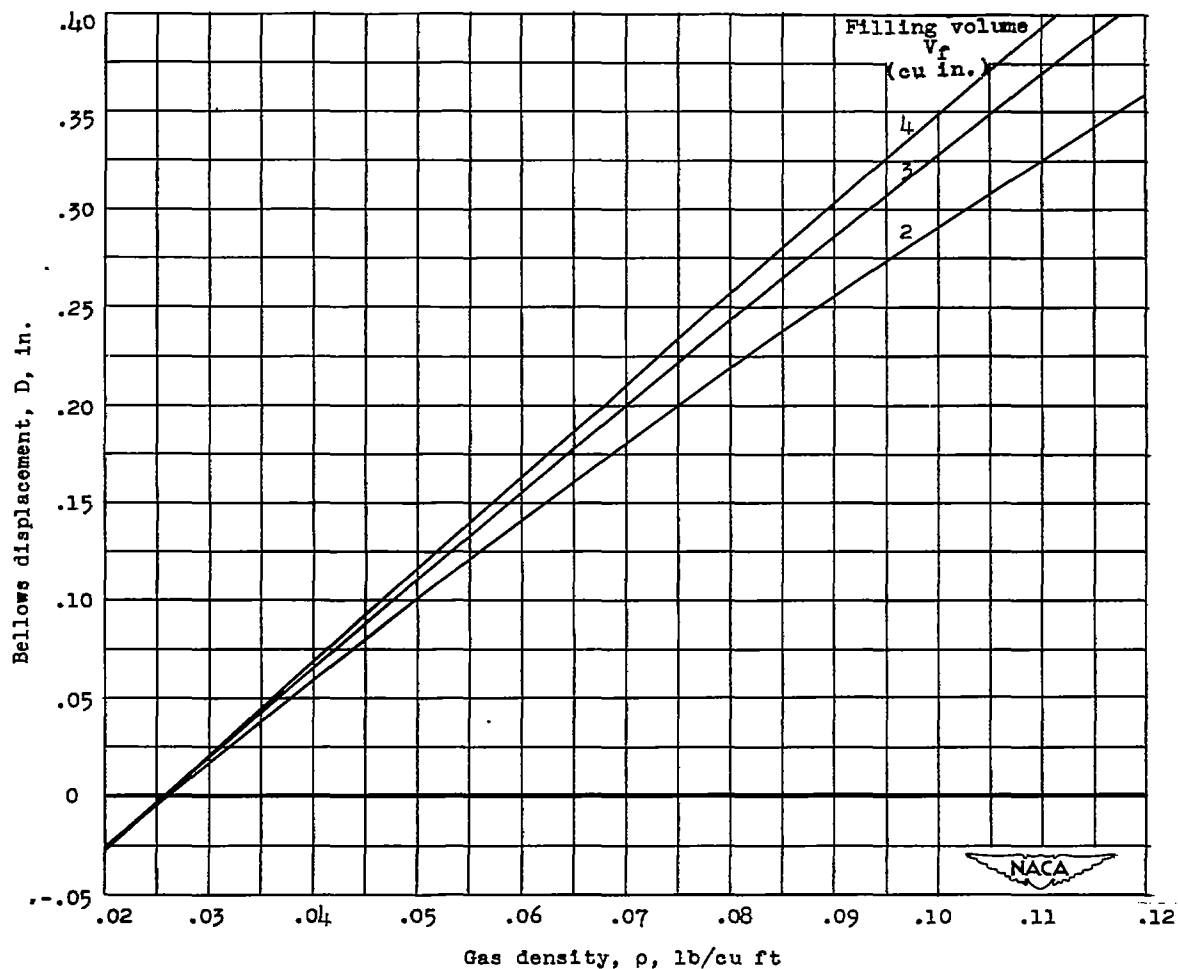
(b) Gas-density - bellows-displacement characteristics at calibration
temperature T_c, 520° R.

Figure 6. — Concluded. Effect of independently varying external spring
rate on error of indication and on gas—density — bellows—displacement
characteristics. Bellows area A, 2 square inches; bellows spring
rate S_b, 50 pounds per inch; preloading distance of external spring
L, 0.4 inch; filling density ρ_f, 0.05 pound per cubic foot; filling
volume V_f, 4 cubic inches; external force F, 2 pounds; gas constant
of gas inside bellows R_i, 55.2 feet per °R; gas constant of gas out—
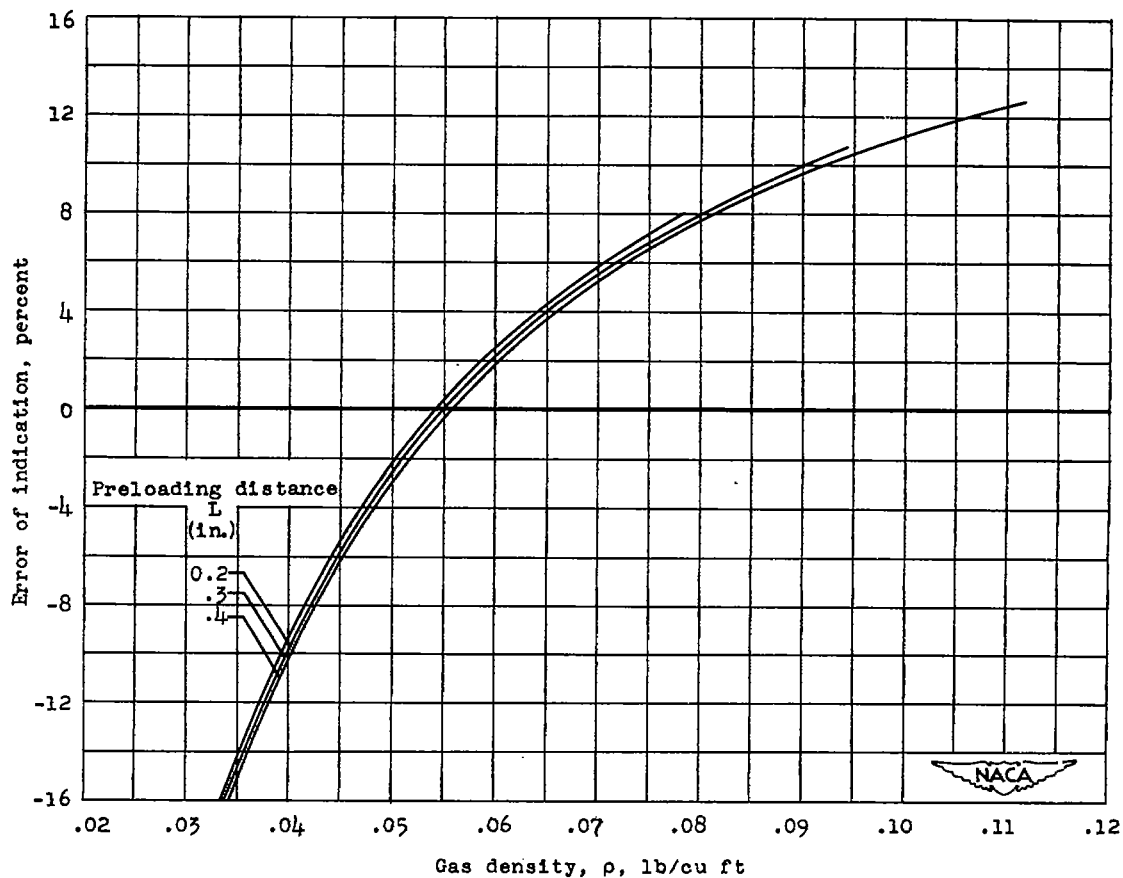side bellows R_o, 53.3 feet per °R.

(a) Error of indication; calibration temperature T_c, 520° R; actual temperature, T_a, 400° R.

Figure 7. — Effect of independently varying filling volume on error of indication and on gas–density — bellows–displacement characteristics. Bellows area A, 2 square inches; bellows spring rate S_b, 50 pounds per inch; external spring rate S_e, 20 pounds per inch; preloading distance of external spring L, 0.4 inch; filling density ρ_f, 0.05 pound per cubic foot; external force F, 2 pounds; gas constant of gas inside bellows R_i, 55.2 feet per °R; gas constant of gas outside bellows R_o, 53.3 feet per °R.
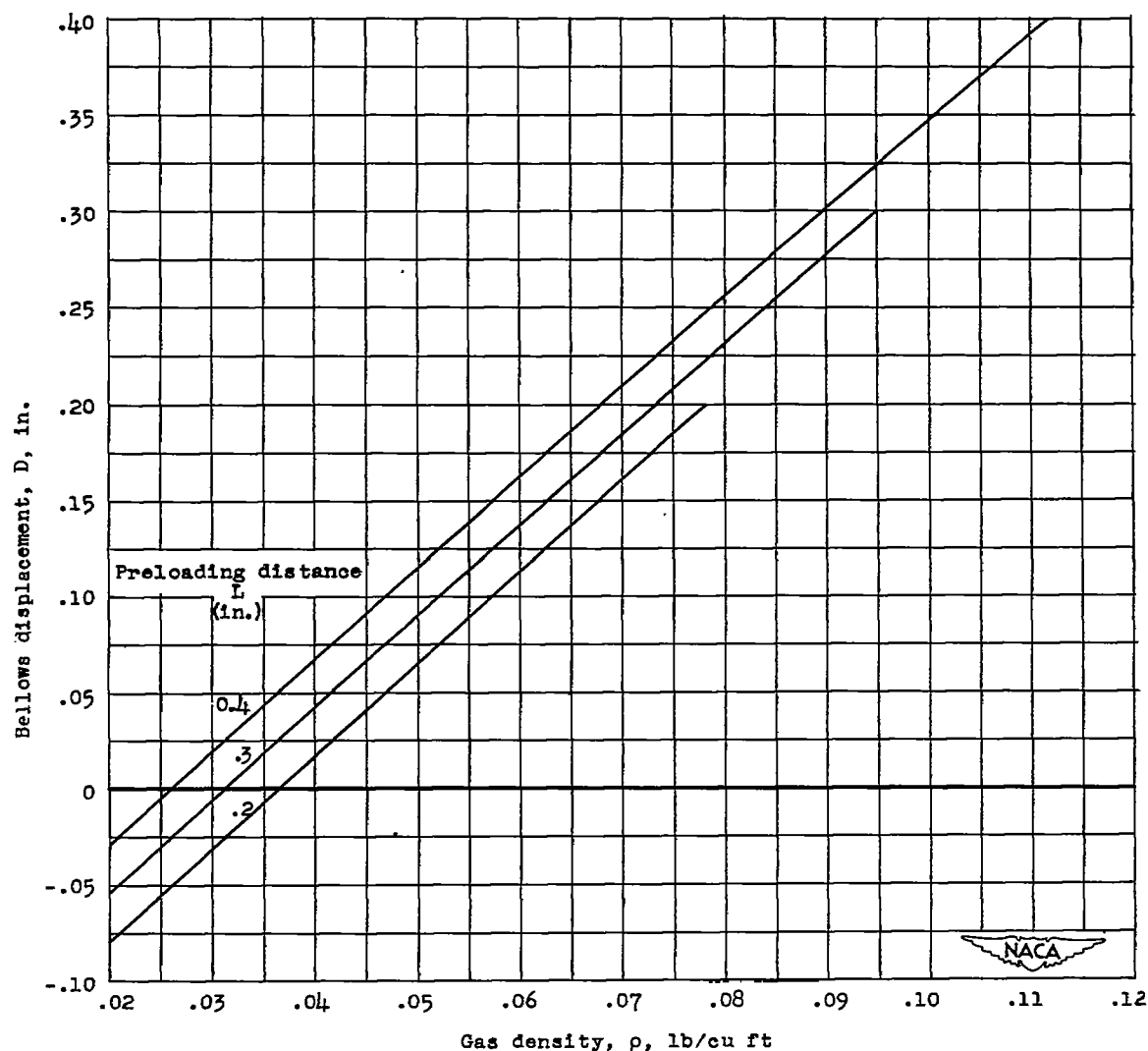
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(b) Gas-density – bellows-displacement characteristics at calibration
temperature T_c, 520° R.

Figure 7. – Concluded. Effect of independently varying filling volume
on error of indication and on gas–density – bellows–displacement
characteristics. Bellows area A, 2 square inches; bellows spring
rate S_b, 50 pounds per inch; external spring rate S_e, 20 pounds per
inch; preloading distance of external spring L, 0.4 inch; filling
density ρ_f, 0.05 pound per cubic foot; external force F, 2 pounds;
gas constant of gas inside bellows R_i, 55.2 feet per °R; gas constant
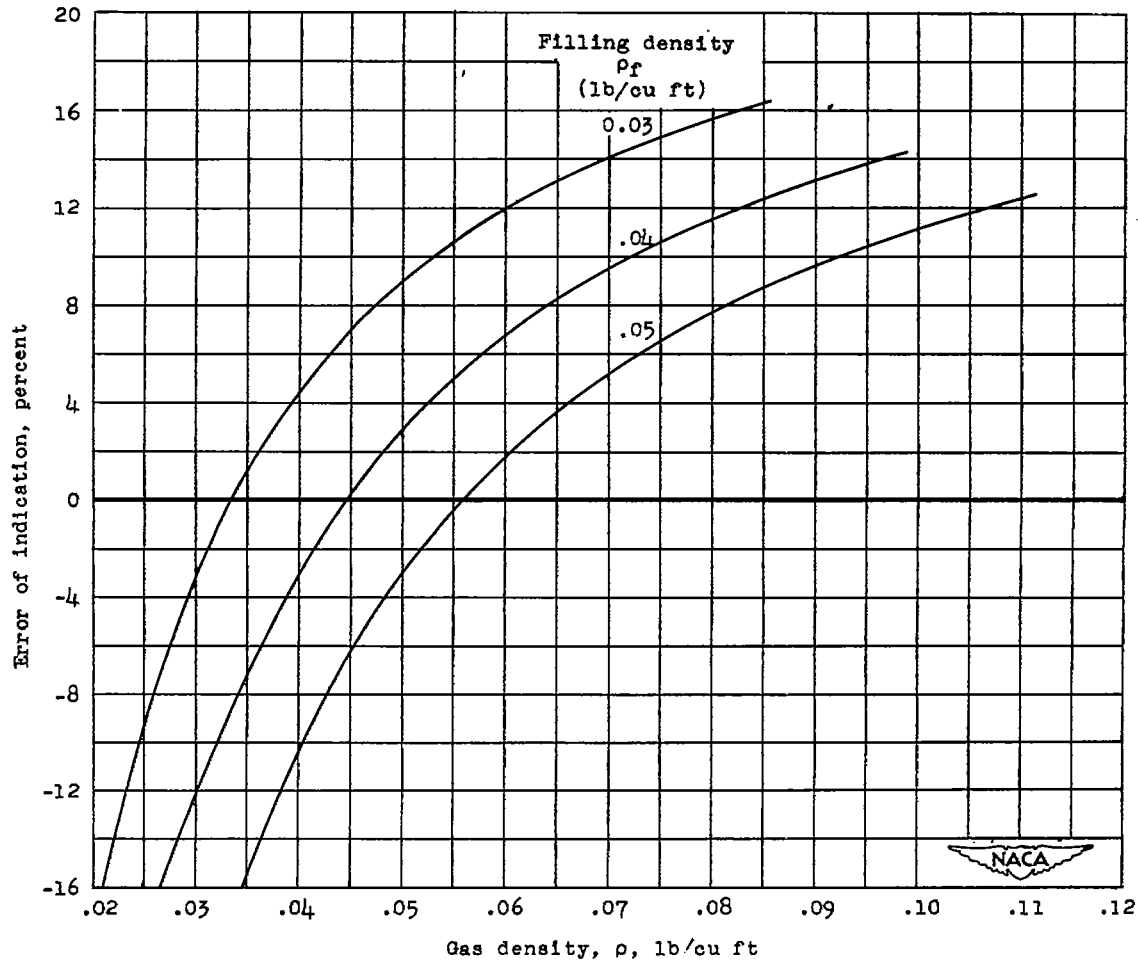of gas outside bellows R_o, 53.3 feet per °R.

(a) Error of indication; calibration temperature T_c, 520° R; actual temperature T_a, 400° R.

Figure 8. — Effect of independently varying preloading of external spring on error of indication and on gas-density — bellows-displacement characteristics. Bellows area A, 2 square inches; bellows spring rate S_b, 50 pounds per inch; external spring rate S_e, 20 pounds per inch; filling density ρ_f, 0.05 pound per cubic foot; filling volume V_f, 4 cubic inches; external force F, 2 pounds; gas constant of gas inside bellows R_i, 55.2 feet per °R; gas constant of gas outside bellows R_o, 53.3 feet per °R.
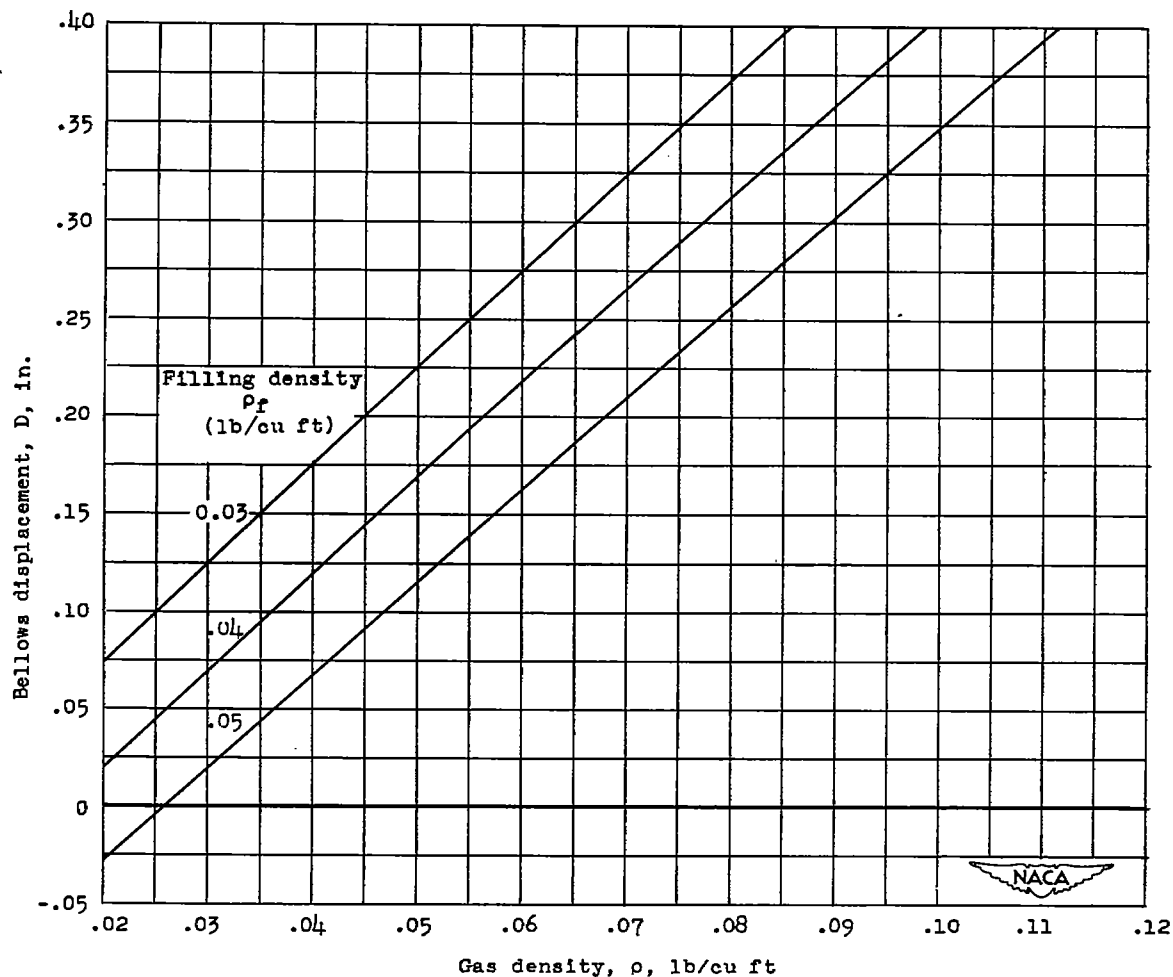
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(b) Gas-density - bellows-displacement characteristics at calibration
temperature T_c, 520° R.

Figure 8. — Concluded. Effect of independently varying preloading of
external spring on error of indication and on gas—density — bellows—
displacement characteristics. Bellows area A, 2 square inches;
bellows spring rate S_b, 50 pounds per inch; external spring rate
S_e, 20 pounds per inch; filling density ρ_f, 0.05 pound per cubic foot;
filling volume V_f, 4 cubic inches; external force F, 2 pounds; gas
constant of gas inside bellows R_i, 55.2 feet per °R; gas constant of
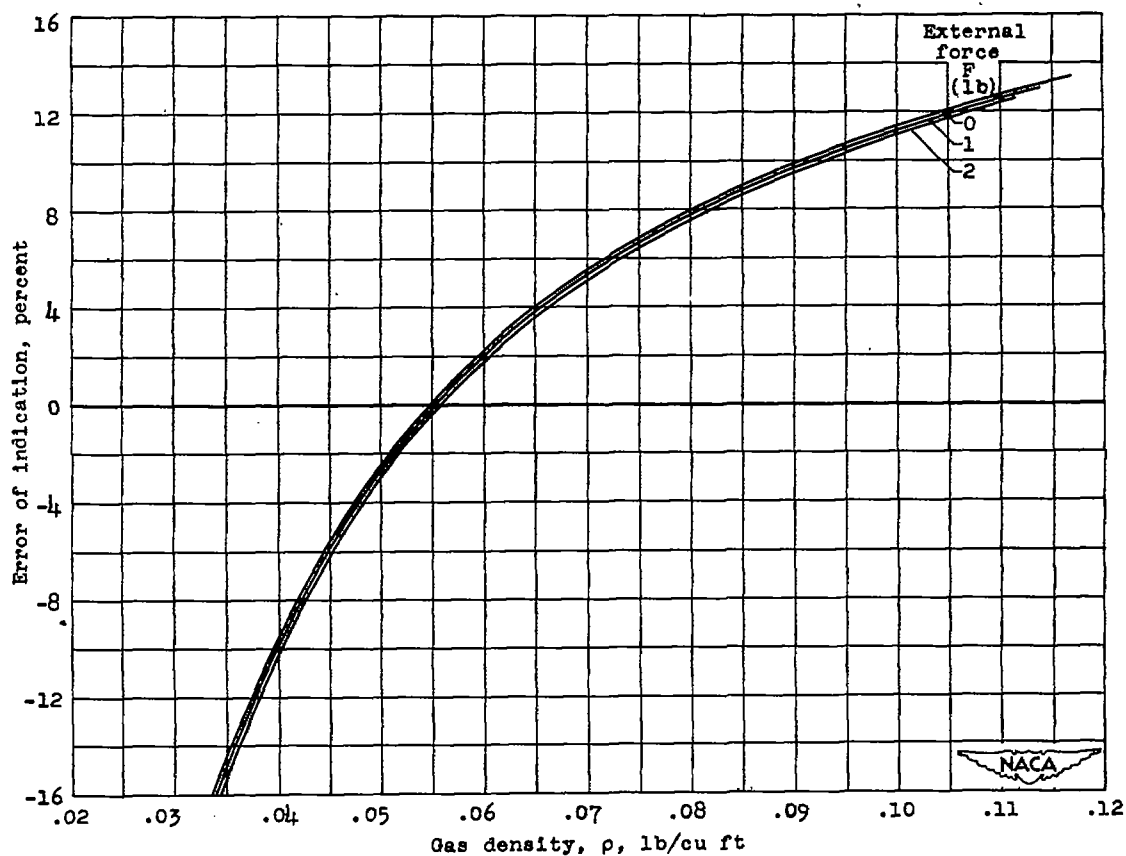gas outside bellows R_o, 53.3 feet per °R.

(a) Error of indication; calibration temperature T_c, 520° R; actual
temperature T_a, 400° R.

Figure 9. — Effect of independently varying filling density on error of indication and on gas-density — bellows-displacement characteristics. Bellows area A, 2 square inches; bellows spring rate S_b, 50 pounds per inch; external spring rate S_e, 20 pounds per inch; preloading distance of external spring L, 0.4 inch; filling volume V_f, 4 cubic inches; external force F, 2 pounds; gas constant of gas inside bellows R_i, 55.2 feet per °R; gas constant of gas outside bellows R_o, 53.3 feet per °R.
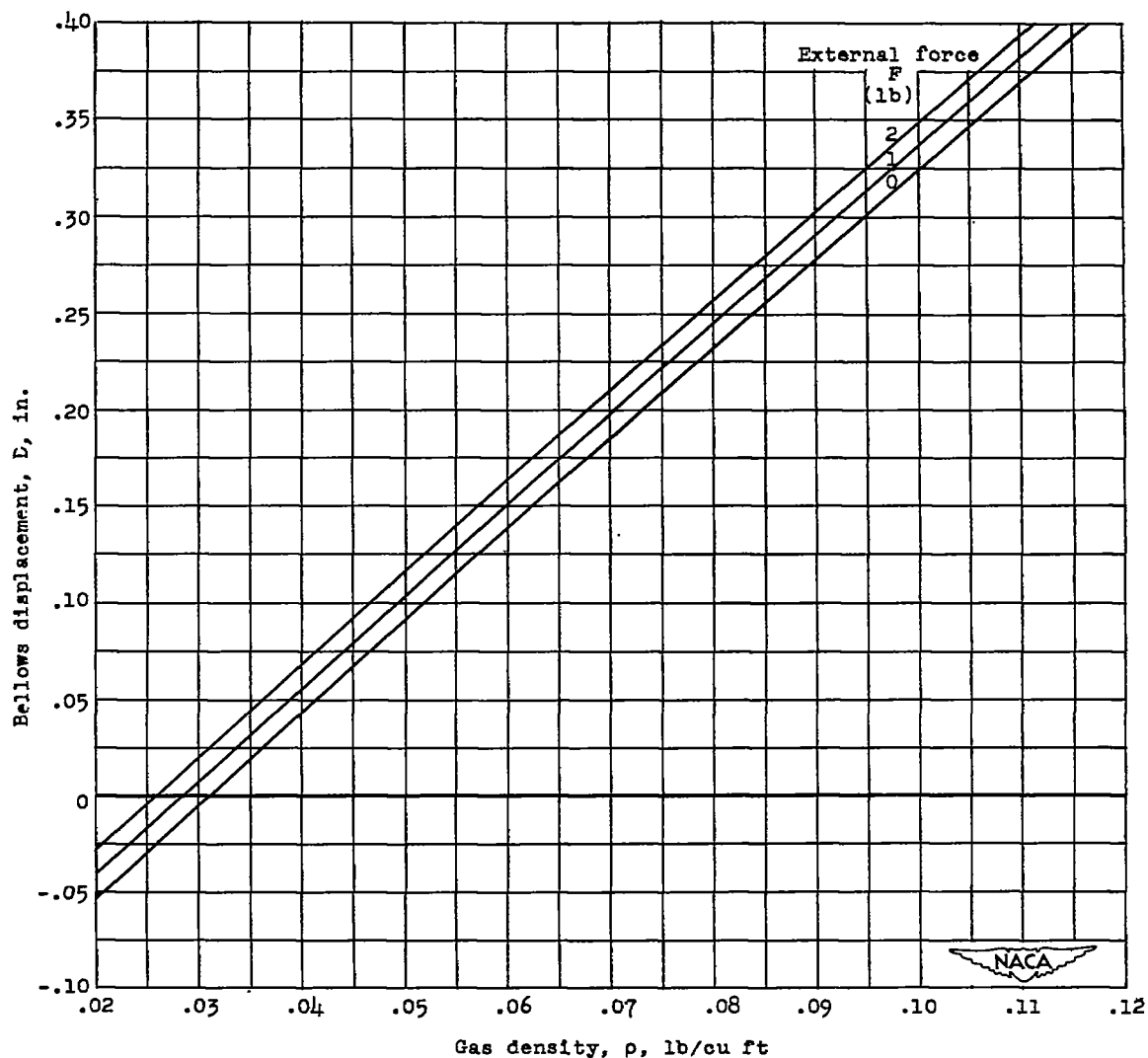
(b) Gas-density - bellows-displacement characteristics at calibration
temperature T_c, 520° R.

Figure 9. — Concluded.   Effect of independently varying filling density
on error of indication and on gas—density — bellows—displacement char—
acteristics.   Bellows area A, 2 square inches; bellows spring rate
S_b, 50 pounds per inch; external spring rate S_e, 20 pounds per inch;
preloading distance of external spring L, 0.4 inch; filling volume
V_f, 4 cubic inches; external force F, 2 pounds; gas constant of gas
inside bellows R_i, 55.2 feet per °R; gas constant of gas outside
bellows R_o, 53.3 feet per °R.

(a) Error of indication; calibration temperature T_c, 520° R; actual temperature T_a, 400° R.

Figure 10. — Effect of independently varying external force on error of indication and on gas-density — bellows-displacement characteristics. Bellows area A, 2 square inches; bellows spring rate S_b, 50 pounds per inch; external spring rate S_e, 20 pounds per inch; preloading distance of external spring L, 0.4 inch; filling density ρ_f, 0.05 pound per cubic foot; filling volume V_f, 4 cubic inches; gas constant of gas inside bellows R_i, 55.2 feet per °R; gas constant of gas outside bellows R_o, 53.3 feet per °R.

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(b) Gas-density - bellows-displacement characteristics at calibration
temperature T_c, 520° R.

Figure 10. - Concluded. Effect of independently varying external force
on error of indication and on gas-density — bellows-displacement char-
acteristics. Bellows area A, 2 square inches; bellows spring rate
S_b, 50 pounds per inch; external spring rate S_e, 20 pounds per inch;
preloading distance of external spring L, 0.4 inch; filling density
ρ_f, 0.05 pound per cubic foot; filling volume V_f, 4 cubic inches; gas
constant of gas inside bellows R_i, 55.2 feet per °R; gas constant of
gas outside bellows R_o, 53.3 feet per °R.